# Characterizing Recent Trends in U.S. Heavy Precipitation

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ABSTRACT

Time series of U.S. daily heavy precipitation (95th percentile) are analyzed to determine factors responsible for regionality and seasonality in their 1979–2013 trends. For annual conditions, contiguous U.S. trends have been characterized by increases in precipitation associated with heavy daily events across the northern United States and decreases across the southern United States. Diagnosis of climate simulations (CCSM4 and CAM4) reveals that the evolution of observed sea surface temperatures (SSTs) was a more important factor influencing these trends than boundary condition changes linked to external radiative forcing alone. Since 1979, the latter induces widespread, but mostly weak, increases in precipitation associated with heavy daily events. The former induces a meridional pattern of northern U.S. increases and southern U.S. decreases as observed, the magnitude of which closely aligns with observed changes, especially over the south and far west. Analysis of model ensemble spread reveals that appreciable 35-yr trends in heavy daily precipitation can occur in the absence of forcing, thereby limiting detection of the weak anthropogenic influence at regional scales.

Analysis of the seasonality in heavy daily precipitation trends supports physical arguments that their changes during 1979–2013 have been intimately linked to internal decadal ocean variability and less so to human-induced climate change. Most of the southern U.S. decrease has occurred during the cold season that has been dynamically driven by an atmospheric circulation reminiscent of teleconnections linked to cold tropical eastern Pacific SSTs. Most of the northeastern U.S. increase has been a warm season phenomenon, the immediate cause for which remains unresolved.

## 1. Introduction

Near the time of the Intergovernmental Panel on Climate Change's (IPCC) First Assessment Report, the body of evidence was already sufficiently compelling to pronounce that a symptom of global warming would be intensification of the global hydrologic cycle involving more heavy precipitation events (IPCC 1992). An increase in heavy precipitation events is among the robust extreme event sensitivities to double $CO_2$ found in early generation climate models (e.g., Noda and Tokioka 1989; Gregory and Mitchell 1995; Cubasch et al. 1995; Mearns et al. 1995). Climate models have improved over subsequent decades, for instance with the median atmospheric resolution of those participating in phase 5 of the Coupled Model Intercomparison Project (CMIP5) ~1° latitude/longitude (e.g., Sillmann et al. 2013), compared to ~4° in models available to the Second Assessment Report (IPCC 1996). While increased resolution alone does not necessarily entail improvement in precipitation, the more realistic depiction of terrain organization of precipitation is a beneficial by-product. Improvements in physical parameterizations, including clouds, radiation, and convection, are important in ongoing research activities (e.g., Klein et al. 2013). Precipitation simulations have improved (e.g., Delworth et al. 2012), although biases at regional scales remain, including an overestimation of the frequency of light precipitation events (e.g., Stephens et al. 2010). Even for models having similar high spatial resolution, model performance in simulating extreme precipitation statistics varies considerably

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(Wehner 2013). Nevertheless, the climate models used in support of the IPCC Fifth Assessment (IPCC 2013) largely affirm the sensitivity of the early generation models concerning anthropogenic forcing of more heavy precipitation events as greenhouse gas forcing increases.

In light of the foregoing evidence of heavy precipitation sensitivity to radiative forcing, this study seeks to better understand the causes and the role of human influence, especially for the recent observed trends (1979–2013) in U.S. heavy precipitation. Investigations of the historical record of daily U.S. precipitation, which have employed different data sources and examined different periods for analysis, are in broad agreement that the northern and eastern United States have experienced statistically significant upward trends in heavy precipitation (e.g., Karl et al. 1995; Groisman et al. 2004; Kunkel et al. 2013). Much of the long-term increase has occurred during the last several decades, which motivates this study's focus period.

For the globe as a whole, observational trends align at least qualitatively with the CMIP5 simulations of contemporaneous effects of radiative forcing and near-term projections. For instance, models indicate that it is likely that heavy precipitation events will increase over many land areas in the near term (2016–35) compared to a recent reference period (1986–2005) (IPCC 2013, see their Table SPM.1). Such a signal is consistent with studies that have formally detected an anthropogenic forcing of the observed increases in extreme daily precipitation over Northern Hemisphere land areas during 1950–2005 (Zhang et al. 2013). This raises the possibility that increases in U.S. heavy precipitation observed in recent decades may already be symptomatic of human influence. The detection and attribution for global conditions thereby undergirds postulations in previous studies that observed changes in U.S. heavy precipitation may be consistent with effects of a warming world (e.g., Karl et al. 1995) and that the occurrences of heavier precipitation over the United States might be understood as resulting from extra water vapor available to storm systems (Melillo et al. 2014).

However, as Kunkel et al. (2013) caution, the causes for these observed trends have not been determined with certainty. Natural variability could also be a factor in heavy precipitation trends over the United States. For instance, Kunkel et al. (2003) found the U.S. frequency of extreme precipitation observed from the late 1800s to the early 1900s to be roughly as high as observed in the 1980s/90s, suggestive of strong internal decadal variability. Likewise, ensemble transient coupled climate simulations show large spread in multidecadal precipitation trends resulting purely from unforced internal variability (e.g., Deser et al. 2014). These lines of evidence raise the possibility that changes in U.S. heavy precipitation observed in recent decades may have been strongly influenced by internal climate variability and may not be symptomatic of human influence alone.

The purpose of this study is to characterize recent trends in heavy daily precipitation over the contiguous United States. We pose the question whether recent observed trends constitute a strongly constrained outcome resulting from sensitivity to radiative forcing. This latter view is implicit in the U.S. National Climate Assessment's explanation of the mechanism driving the observed increase in heavy downpours, which indicates that the amount of water vapor in the atmosphere has increased as a result of human-induced warming and that "this extra moisture is available to storm systems, resulting in heavier rainfalls" (Melillo et al. 2014, p. 25). Our analysis begins by examining the observational time series of heavy precipitation for the 1901–2013 record and then places changes during recent decades into the longer historical context. Using coupled model simulations [NCAR's Community Climate System Model (CCSM4)], we next examine the extent to which trends since 1979 have been caused by human influence. The detectability of an externally driven change is assessed using large ensemble methods in which the signal of externally forced change is compared to the magnitude of inherent noise resulting from coupled ocean–atmosphere variability. Physical characteristics of internal variations that may have contributed to recent observed trends in heavy precipitation are next examined using additional atmospheric model simulations [NCAR Community Atmosphere Model, version 4.0 (CAM4)].

Our results reveal a large spread in 1979–2013 heavy precipitation trends among identically forced ensemble members of historical coupled simulations, indicating that particular traces of internal coupled ocean–atmosphere variability could be especially relevant for interpreting recent observed trends. Diagnosis of historical atmospheric model simulations [Atmospheric Model Intercomparison Project (AMIP)] reveals an important impact of the particular history of observed sea surface temperature (SST) in forcing U.S. heavy precipitation trends. By studying the regionality and seasonality of observed and model-simulated heavy precipitation trends, physical arguments are provided that support a view that recent atmospheric trends have been strongly forced, though less by human-induced climate change than by internal decadal ocean variability.

Section 2 introduces the observed dataset and model simulations utilized in the study. Section 3 describes the results. Section 4 summarizes our characterization of the recent trends in U.S. heavy precipitation.

## 2. Datasets

### a. Observed daily precipitation and defining very wet days

The individual station observations are extracted from the Global Historical Climatology Network-Daily database (GHCN-D; Menne et al. 2012). Daily precipitation observations are only used if the station site was operating for at least 50 years and had 80% availability during the period 1901–2013. A total of about 10 000 stations with daily precipitation are retained in our analysis. To facilitate comparisons with the model(s), individual sites are gridded onto a model grid of 0.94° × 1.25° over the continental United States using an inverse distance weighting technique. An area-weighted average of all grid points is then created for each of nine climatic regions as provided by the National Climatic Data Center (see Karl and Koss 1984). Subsequent analysis, including trends, is then generated from the respective regional area averages. At the scales examined herein, and given the abundance of daily data, our results are not sensitive to the details of the gridding procedure.

Heavy daily precipitation events, also referred to as very wet days, are those days exceeding the 95th percentile of precipitation falling on a wet day precipitation occurrence exceeding 1 mm (Sillmann et al. 2013). We calculate the 95th percentile threshold from a 1901–78 historical period. The number of events exceeding that threshold, and the cumulative amount of precipitation exceeding that threshold, is then computed for each year from 1979–2013, and linear trends are calculated. The analysis is conducted for annual data and also separately for warm season (May–October) and cold season (November–April) half years.

### b. Model simulations

Daily precipitation data are extracted from five different sets of 20-member ensemble climate simulations, summarized in Table 1. One set is based on historical transient simulations of a coupled model (CMIP style) using the fourth version of NCAR's CCSM4 (Gent et al. 2011). The specified external forcings consist of greenhouse gases (e.g., $CO_2$, $CH_4$, $NO_2$, $O_3$, and CFCs), aerosols, solar, and volcanic aerosols with the RCP6.0 scenario used for the simulation period after 2005. As part of this study, a 20-member ensemble of CCSM4 transient runs was conducted spanning the period 1970–2014, for which we treat the period from 1970–78 as spinup. The 20 members were derived from of a single long "seed" transient simulation of CCSM4, which had begun in 1850, by perturbing atmospheric initial conditions in 1970.

TABLE 1. Overview of model experiments.

| Expt | Period | SST/sea ice | Ensembles |
|---|---|---|---|
| CCSM4 | 1970–2014 | Coupled | 20 |
| | 1871–2005 | | 2 |
| CAM4-O | 1979–2014 | Specified; observed | 20 |
| | 1871–2005 | | 2 |
| CAM4-C | 1979–2014 | Specified; CCSM4 | 20 |
| | 1871–2005 | | 2 |
| CAM4 trace 2 scenarios | 1979–2014 | Specified; CCSM4 SST shown in Fig. 6 | 20 |

We also have conducted four sets of historical AMIP-style simulations in which temporally evolving lower-boundary conditions (SST and sea ice) are prescribed. The experiments are subjected to daily evolving lower-boundary conditions, which have been linearly interpolated from the appropriate monthly SST/sea ice values. These historical simulations use the atmospheric component of CCSM4 [CAM4 with horizontal resolution 0.94° × 1.25° and 26 vertical levels (Gent et al. 2011)] with time-varying external forcings that are identical to those used in the CCSM4 runs.

The first 20-member AMIP ensemble spans 1979–2014 and is forced by observed monthly varying SST and sea ice from the Hurrell et al. (2008) dataset. These experiments are subsequently referred to as CAM4-O. Three additional AMIP-style ensembles are performed that are forced by monthly SST and sea ice variations extracted from the CCSM4 transient runs. In one suite, a 20-member ensemble is conducted for which each of the individual runs utilize the SST and sea ice variations of one of the 20 CCSM4 experiments. The purpose of these CAM4-C experiments is to compare with the parallel CCSM4 runs and assess biases that can arise when diagnosing regional heavy precipitation trends occurring in a coupled system but using an atmospheric modeling (AMIP; Atmospheric Model Intercomparison Project) approach. The other two suites use two particular SST and sea ice time series extracted from the CCSM4 experiments and for which a 20-member AMIP-style ensemble is performed. Two different model SST histories (subsequently referred to as a "trace" to denote the particular path of the ocean taken in the simulation) are selected. One trace of the coupled model was selected because it resembles the low-frequency SST change pattern observed during 1979–2014, particularly an ENSO-like decadal variation consisting of slight cooling in the equatorial eastern Pacific (see Fig. 6). A second trace was selected because it resembles the more typical history of the coupled model's behavior, resembling the ensemble mean SST response pattern to radiative forcing change during this period. The purpose here is to assess the importance of particular SST/sea ice traces for

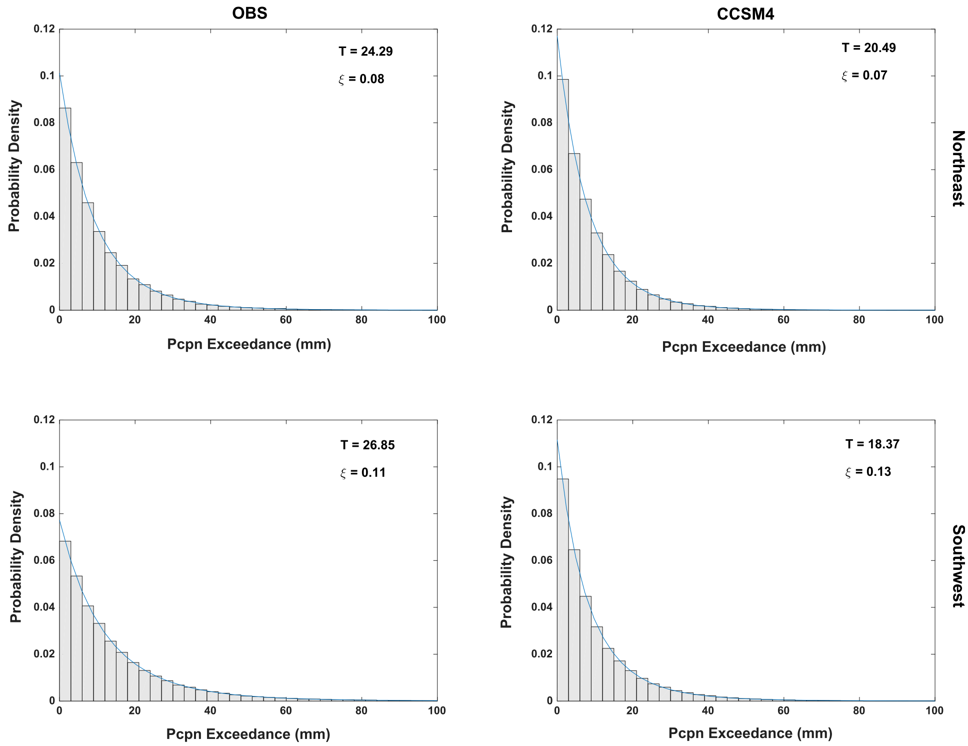


FIG. 1. Frequency distributions of (left) daily observed and (right) daily CCSM4-simulated precipitation exceedances (mm) for events above the 95th percentile threshold of all daily totals. Period of analysis is 1901–78. Shown are spatial averages for the (top) northeast and (bottom) southwest U.S. regions (see Fig. 2 for locations). Listed values in the inset indicate the 95th percentile threshold of daily precipitation $T$ (mm) and the shape parameter $\xi$ of the GPD (smooth curve) that has been fit to the empirical data. Positive values for $\xi$ denote a heavy tail for extreme wet days (relative to an exponential distribution). Shown are exceedance values from 0 to 100 mm, although there are a few daily exceedances as high as 250 mm.

driving regional heavy precipitation trends, recognizing that the differences between each of those traces is solely due to the coupled model's internal variability. These runs, referred to as ''trace experiments,'' are also useful for interpreting the CAM4-O simulations in which the particular observed SST/sea ice trace was specified.

For each of the CCSM4, CAM4-O, and CAM4-C experiments, we also have two runs available that span the period from 1871 to 2005. We use these long runs to evaluate the long-term climatological statistics of daily precipitation of the coupled CCSM4 and atmospheric CAM4 (both for observed and CCSM4-derived lower-boundary conditions), described below.

## 3. Results

### *a. Climatological observed and simulated daily precipitation*

In this study, observations and all model daily precipitation data are spatially averaged for the nine U.S. climate regions. The threshold for the 95th percentile of daily precipitation is derived separately for the observations and the long model simulations, based on their respective 1901–78 reference periods. Figure 1 compares the frequency distributions of observed and simulated extreme daily precipitation (exceeding the 95th percentile of daily values) for two different geographical regions, a relatively wet northeastern U.S. domain (top) and the drier southwestern domain (bottom). The geography of these regions is identified in Fig. 2. Shown is the generalized Pareto distribution (GPD) for daily precipitation exceeding a 95th percentile. The GPD provides a good parametric fit to both the model and observed data. The shape parameter $\xi$ is positive for both regions and for both datasets, indicative of a heavy tail behavior. The results highlight the different regional characteristics of extreme daily precipitation, with a heavier tail behavior (i.e., larger value for the GPD shape parameter) over the southwest than over the northeast United States. There is thus a greater enhancement of probabilities for extreme daily values in the southwest compared to the northeast United States.

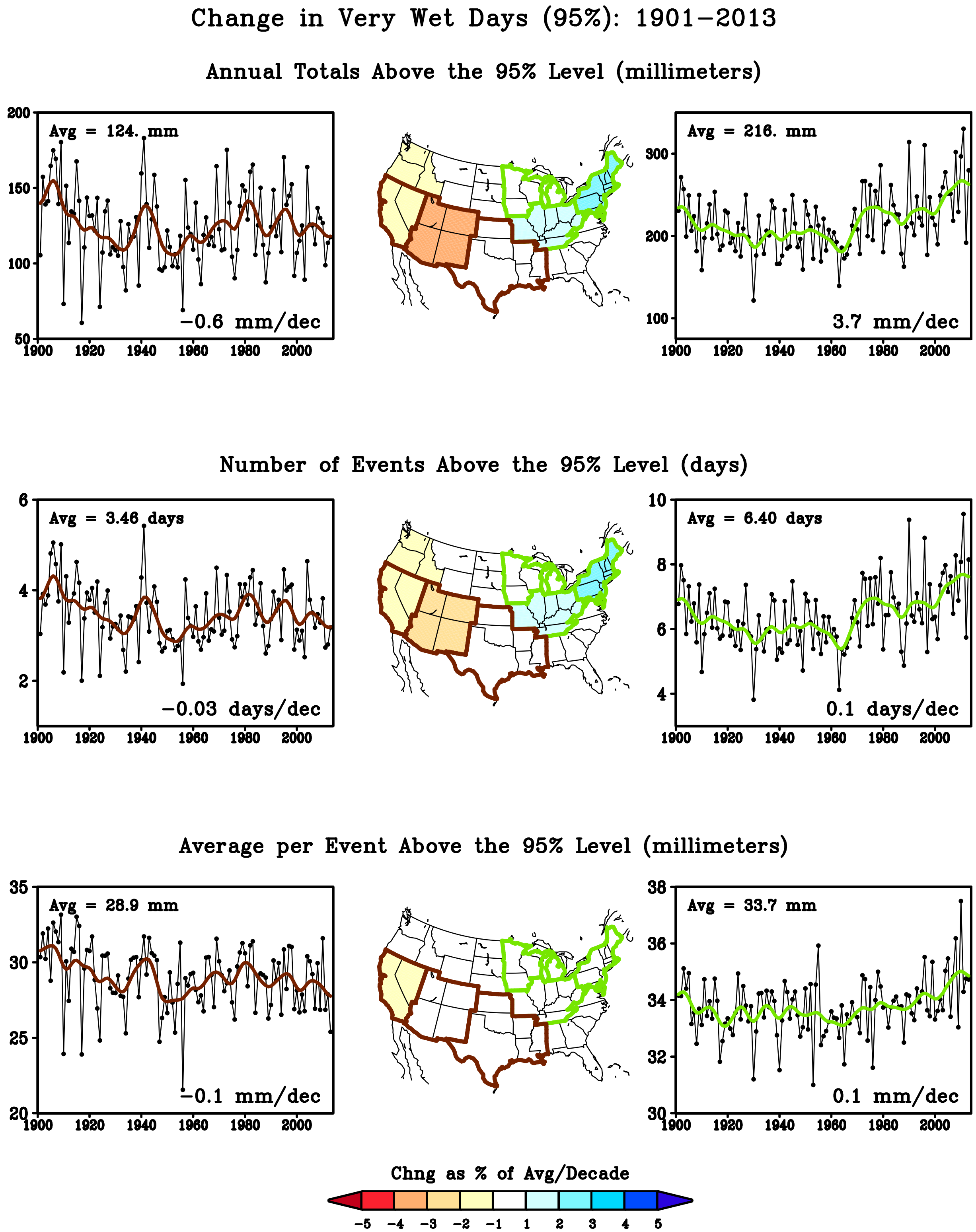


FIG. 2. The observed 1901–2013 change in (top) annual precipitation (mm) associated with heavy daily events (upper 5%), (middle) number of heavy daily precipitation events, and (bottom) average precipitation (mm) per heavy daily event. Maps show change expressed as % decade$^{-1}$. Adjacent time series, for each of the three characteristics of heavy precipitation, are calculated for an area average of three climate regions referred to as (left) the Southwest and (right) the northeast United States. Regional outlines in the maps indicate the climate regions used to construct the time series. The curve on each time series is a 9-point Gaussian filter applied to annual values. Trend values (decade$^{-1}$) are indicated in the lower right.

The CCSM4 simulation replicates this observed regional dependency of positively skewed daily precipitation extreme quite well. However, the model has a notable bias in its 95th percentile threshold values ($T$), being lower compared to observed in both regions. The model does exhibit a realistic heavy tail behavior, though the smaller value for the shape parameter compared to observed is statistically different by comparing 95th percentile uncertainty intervals for the estimated shape parameter. These strengths and limitations of the CCSM4 simulations of daily precipitation are found to arise in the other historical simulations of this study, regardless of whether one is using coupled or uncoupled simulations, or specified observed or specified CCSM4 SST/sea ice variability (not shown). These model biases generally mimic those found in current generations of global climate models, as described in the introduction.

### *b. Observed annual trends during 1901–2013*

Various characteristics of precipitation change during the longer 1901–2013 period are first presented (Fig. 2) in order to provide context for our subsequent analysis of trends during 1979–2013. Principal features of long-term change are increases in precipitation associated with heavy daily events over the northeast United States and decreases over the southwest United States (top). Similar regionality in long-term trends of heavy daily precipitation was identified by Groisman et al. (2004) for a 1908–2000 period and by Kunkel et al. (2013) for a 1901–2010 period. In particular, both prior studies emphasize that long-term upward trends for the United States as a whole have arisen mainly from strong regional increases over eastern and northern portions of the United States.

The temporal evolution of annual precipitation associated with heavy daily events averaged across a greater northeastern and southwestern region (identical to the regions used in the Fig. 1 analysis) is shown in the left- and right-side time series of Fig. 2, respectively. The time series over the U.S. Northeast in particular reveals a comparatively steady increase in annual precipitation falling in heavy events over the last half century. Such an upward trend over the last half century has previously been shown to be statistically significant (see Table 1 in Kunkel et al. 2013). We find that the 1901–2013 linear trends for the various properties in daily very wet day changes are significant at 99% for the greater northeastern region, whereas the trends are not significant at that level for the greater southwestern region.

The 1901–2013 trends in annual precipitation falling in heavy events have resulted from both changes in their frequency (Fig. 2, middle panels), and in the amount of precipitation per event (lower panels). In particular, both the frequency and the intensity of heavy rain events have increased (decreased) over the U.S. Northeast (U.S. Southwest). Karl and Knight (1998) provided a similar characterization of precipitation trends based on their analysis of changes in amount, frequency, and intensity for daily extremes in the United States during 1910–95. Our analysis uses a simple definition for precipitation intensity based on the ratio of total precipitation (Fig. 2, top) to number of events (Fig. 2, middle), for which prior studies have indicated no detectability of change in the United States (e.g., Karl et al. 1995). A more comprehensive assessment of precipitation intensity, for example maximum hourly rates, is beyond the scope of this study.

Finally, although the results in Fig. 2 are for a particular threshold value for daily precipitation, we note that similar characteristics of precipitation change on a national scale have been identified for various intensities of daily precipitation ranging from the 95th percentile to the 99.9th percentile (see Table 2 of Groisman et al. 2004). Some regional features of trends may be sensitive to the use of different threshold categories, as shown for instance in Karl and Knight (1998). We have conducted our analysis for the 1901–2013 period for the 90th, 95th, and 99th percentiles and find qualitatively similar results.

### *c. Observed and simulated annual trends during 1979–2013*

Figure 3 compares observed trends in heavy precipitation during 1979–2013 with the ensemble mean trend patterns in various historical climate simulations. We focus on the changes in annual precipitation totals (% decade$^{-1}$, left panels) falling on very wet days, which stem principally from changes in event frequency (middle panels) and less from a change in the intensity of precipitation during very wet days in both observations and simulations (right panels).

The observed precipitation change pattern since 1979 (Fig. 3, top) is similar to the long-term change pattern since 1901—increases dominate the northern United States and decreases dominate the southern United States (cf. Fig. 2). The largest magnitude changes, though of opposite sign, have occurred over the far northeast and far southwest, where the total 35-yr change has been about 30%.

Analysis of the various historical simulations indicates that the observed trends have been strongly forced, with an intercomparison of CMIP and AMIP simulations clarifying the nature of that forcing. The effect of the time-evolving external radiative forcing increases annual precipitation associated with heavy daily events over most of the contiguous United States (Fig. 3, second panel). This signal in CCSM4 is consistent with

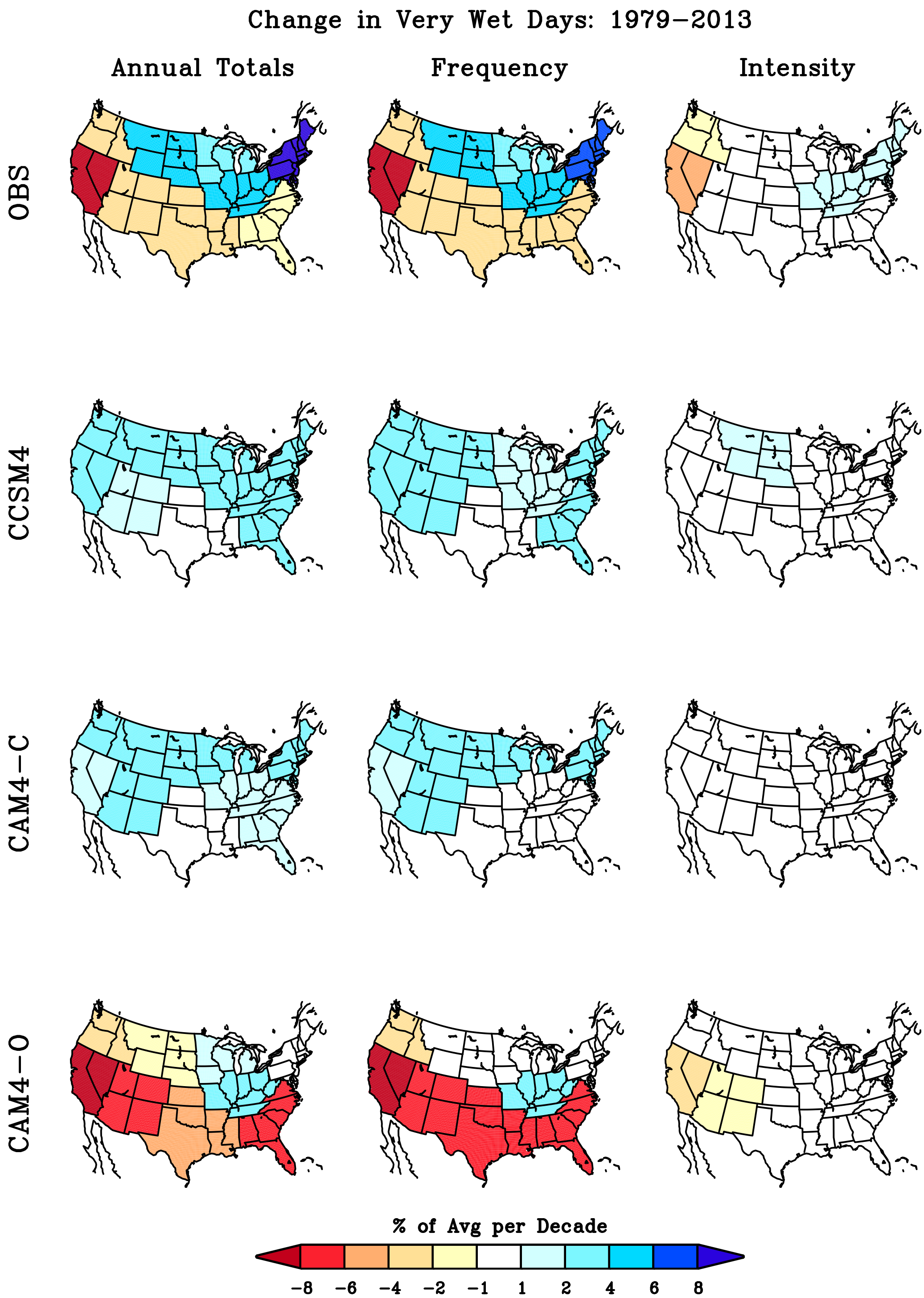


FIG. 3. The 1979–2013 changes in (left) annual precipitation associated with heavy daily events (upper 5%), (middle) frequency of very wet days, and (right) precipitation intensity on very wet days. Results compare (top) observations, (upper middle) CCSM4, (lower middle) CAM4-C, and (bottom) CAM4-O historical simulations. Maps show change expressed (% decade$^{-1}$). The model trends are based on 20-member ensemble means for each configuration. See Table 1 for description of experiments.

evidence for human influences on observed global increases in annual maximum daily precipitation (e.g., Zhang et al. 2013; Westra et al. 2013). Over the northern United States, where heavy precipitation has been trending upward, the increases associated with external forcing are generally a factor of 2 weaker than observed trends. The signal of external forcing does not explain the opposite-signed changes that have occurred between northern and southern sections. Symptomatic of the poor spatial agreement, the congruence (see, e.g., Guirguis and Avissar 2008) of the observed change pattern and the CCSM4 ensemble mean signal is only 0.1 for the contiguous United States as a whole.

By further constraining the historical simulations by specifying observed SST variations (in addition to specifying radiative forcing changes), the CAM4-O results (Fig. 3, bottom) yield a better spatial agreement with the observed trend pattern. The congruence with the observed change pattern is 0.7 for the contiguous United States as a whole. We note that the CAM4-O simulations capture the strong ~30% decline in heavy precipitation observed over the far southwest, although there is no appreciable sensitivity of annual heavy precipitation over the far northeast.

Overall, the particular trajectory of observed SSTs appears to have more strongly influenced trends in observed heavy precipitation since 1979 than has the particular trajectory of external radiative forcing. The substantial differences between the CCSM4 and CAM4-O patterns indicate that key elements of the observed SST variations responsible for heavy precipitation trends over the United States are themselves unlikely to be a consequence of external radiative forcing. To further quantify these differences between the historical simulations, Fig. 4 presents the congruence coefficients between the observed trend pattern and each of the ensemble members of the model experiments. The frequency distributions of the 20 CAM4-O simulated trend patterns are illustrated by the green curve, and distributions associated with the CCSM4 runs are illustrated by the red curve. While no single run of any of the model simulations yields a trend pattern that is virtually identical to observations (i.e., $r_c > 0.90$), the CAM4-O members have a consistently high level of spatial agreement, whereas the CCSM4 members do not. Further, the smaller spread among CAM4-O ensemble members compared to CCSM4 indicates the stronger constraint on the U.S. trend pattern imposed by the observed SST trajectory than by the observed trajectory of external radiative forcing alone.

The results indicate a large sensitivity of regional heavy precipitation trends to global SST boundary forcing. To test the reliability of this finding, especially in the context of whether a two-tiered AMIP methodology offers reliable diagnosis of forcing–response relationships occurring in the coupled climate system, additional experiments have been conducted. Figure 3 (third panel) presents the simulated trends in U.S. heavy precipitation in an AMIP approach by specifying the varying SST and sea ice from CCSM4 in addition to the time-evolving external radiative forcing (see Table 1 and section 2 for further details). It is evident from the similarity between the CCSM4 and CAM4-C trend patterns ($r_c = 0.9$) that the AMIP approach has not introduced appreciable biases in the representation of the coupled system sensitivity to forcing, thereby giving us confidence in applying that approach to understanding the observed coupled system. In subsequent analyses, we will further explore the importance of particular, plausible traces in global SSTs that can arise under the influence of identical external forcing and isolate the sensitivity of regional U.S. precipitation change patterns to such traces using an AMIP approach.

Figure 5 summarizes historical simulation statistics of 35-yr trends in heavy precipitation for the greater northeast (top) and greater southwest (bottom) U.S. regions (see map outlines in Fig. 2 for area definitions). Over the northeast, the frequency distributions of both model ensembles are shifted toward increased heavy precipitation. The mean signal is small (~+2% decade$^{-1}$) compared to the standard deviation among ensemble members (~3% decade$^{-1}$). The results for the

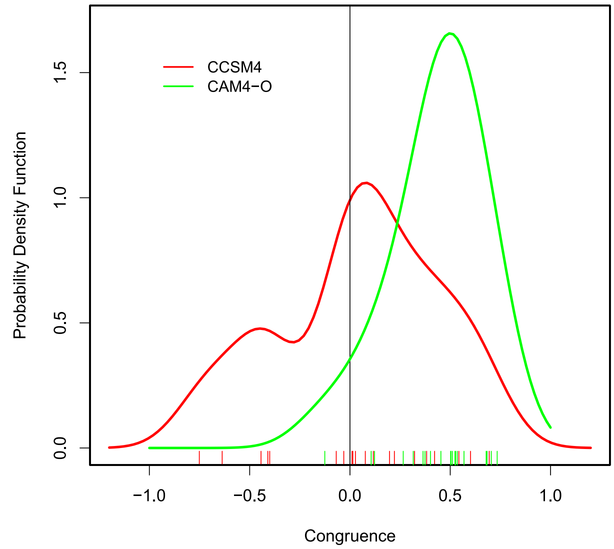


FIG. 4. The congruence coefficient $r_c$ for the spatial agreement between observed 1979–2013 U.S. trends in heavy precipitation and simulated trends in CCSM4 (red ticks) and CAM4-O (green ticks) historical experiments. The red (green) smooth curve is the nonparametric estimate of the frequency distribution for the CCSM4 (CAM4-O) 20-member simulations.

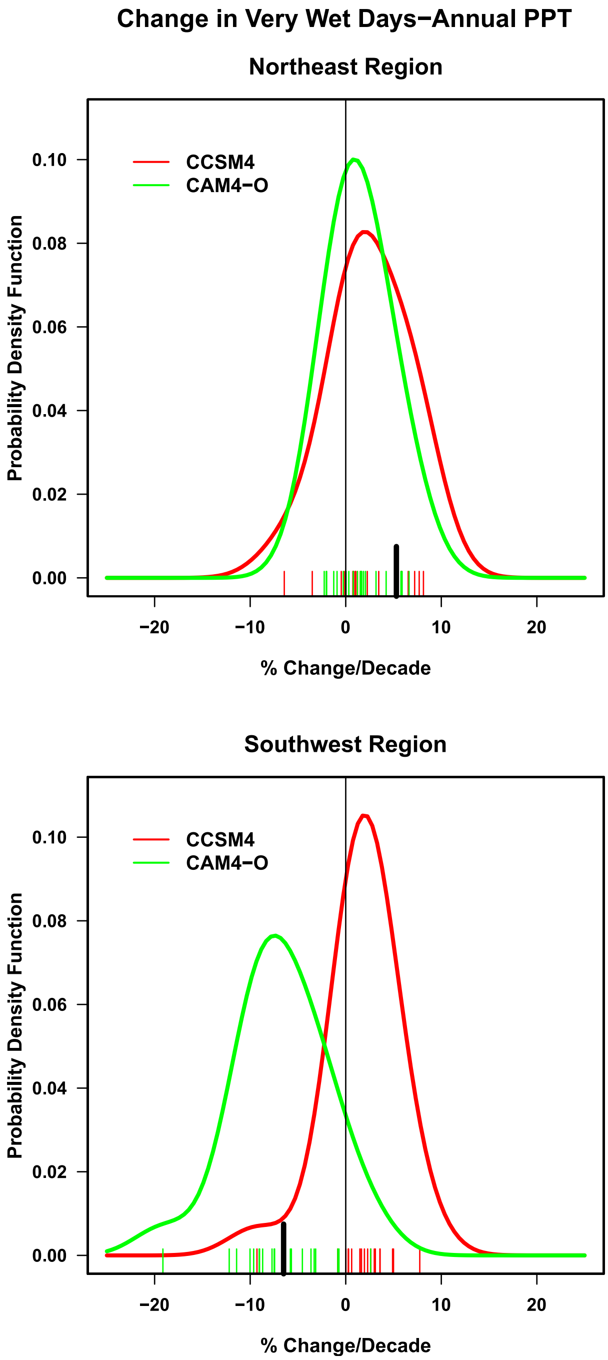


FIG. 5. Frequency distributions of 1979–2013 trends in regional precipitation (PPT) for the (top) northeast and (bottom) southwest U.S. region for CCSM4 (red) and CAM4-O (green) historical simulations. Smooth curves are the nonparametric estimates of the frequency distributions. Small tics denote each of the 20 simulated trend values, and the large gray tic is the observed trend value.

northeast thus imply low detectability of a forced signal of change since 1979, either resulting from radiative forcing alone or also including the observed SST forcing. The comparatively large magnitude of the observed increase in heavy precipitation over the northeast (+5% decade$^{-1}$) is thus unlikely to be reconcilable with a forced component alone but is more likely dominated by an appreciable unforced component of change since 1979.

For the effect of external radiative forcing alone, there is little difference in the statistics of CCSM4-simulated 35-yr heavy precipitation trends over the northeast and southwest (cf. top and bottom panels of Fig. 5). In contrast, as a consequence of the additional effect of observed SST forcing, there is appreciable difference in impacts over the two regions; all but one of the 20 members of CAM4-O simulations produce downward trends in heavy precipitation over the southwest (Fig. 5, bottom, green curve). The mean signal in CAM4-O is −7% decade$^{-1}$, which agrees well with the observed decline of −7% decade$^{-1}$. Again, as for the northeast region, there is appreciable noise in 35-yr trends owing to unforced atmospheric variations alone. However, the AMIP results indicate that the forced component of heavy precipitation change related to the particular history of SST variability is highly detectable over the southwest, being twofold greater in magnitude than the internal atmospheric-driven noise of 35-yr trends.

Given our evidence that the annual pattern of observed U.S. heavy precipitation changes since 1979 has been strongly influenced by SST forcing, but only weakly by external radiative forcing and its attending ocean changes (based on the spatial congruence analysis for patterns of heavy precipitation trends over the contiguous United States in Fig. 4), we contrast the observed SST change (Fig. 6, top) with CCSM4's SST response to radiative forcing (Fig. 6, second panel). Both describe widespread warming of the world's oceans, with the exception that a cooling trend since 1979 has been observed over the tropical central-eastern Pacific. This observed pattern resembles the cold tropical phase of ENSO-like Pacific decadal variability, which can arise from internal coupled air–sea interactions (e.g., Zhang et al. 1997). Consistent with such an interpretation, we note the considerable intersample variability of the 1979–2013 SST trend pattern in CCSM4. Figure 6 provides two examples: one member that yields a trend closely resembling the model's ensemble mean response (Fig. 6, trace 10) and another member showing a pattern of simulated change more consistent with the observed change pattern (Fig. 6, trace 14). That a member of CCSM4 integrations can generate a multidecadal period devoid of warming in the equatorial eastern Pacific under increasing radiative forcing is not surprising, having been previously noted by Meehl et al. (2011), who found decadal-scale tropical eastern Pacific Ocean cooling in a single member of future twenty-first-century CCSM4

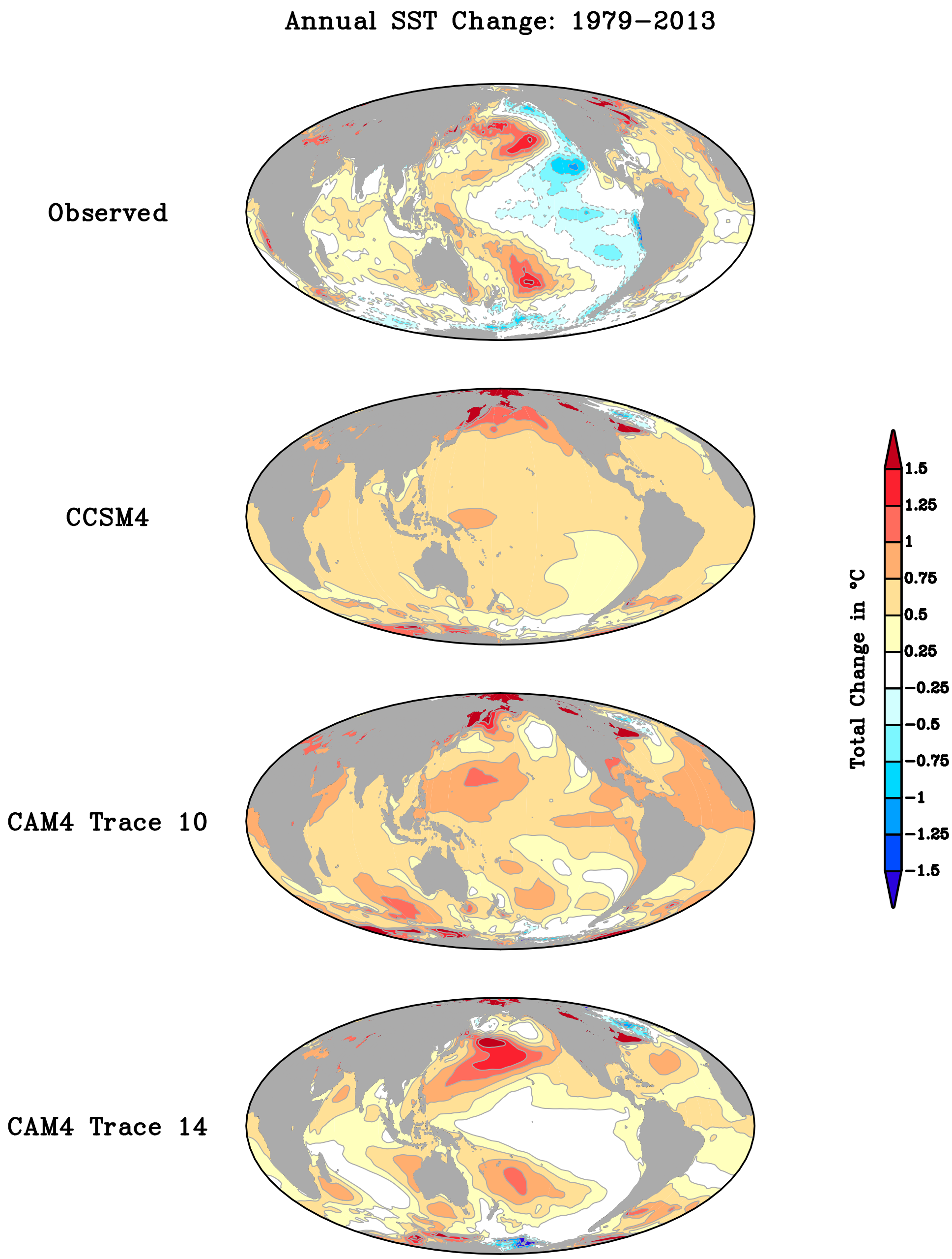


FIG. 6. The 1979–2013 trends in annual sea surface temperatures [°C (35 yr)$^{-1}$] (top) observed, (upper middle) ensemble-averaged simulation in 20-member CCSM4, (lower middle) simulated in individual member 10 of CCSM4, and (bottom) individual member 14 of CCSM4.

projections, which they interpreted as due to internally generated variability.

Using these two scenarios, the additional ensembles of AMIP-style simulations driven by the SST histories of these two CCSM4 traces are diagnosed, the results of which are presented in Fig. 7. Our purpose is to probe more thoroughly the sensitivity of U.S. heavy precipitation change to various plausible SST scenarios during 1979–2013, each consistent with identical external radiative forcing during this time. The experiments are also a tool to support a physical explanation for the dramatic differences between CCSM4 and CAM4-O ensemble mean signals of U.S. heavy precipitation change (see Fig. 3). The top panels of Fig. 7 compare the 20-member ensemble mean simulated trends in annual heavy precipitation subjected to trace 10 (left) and trace

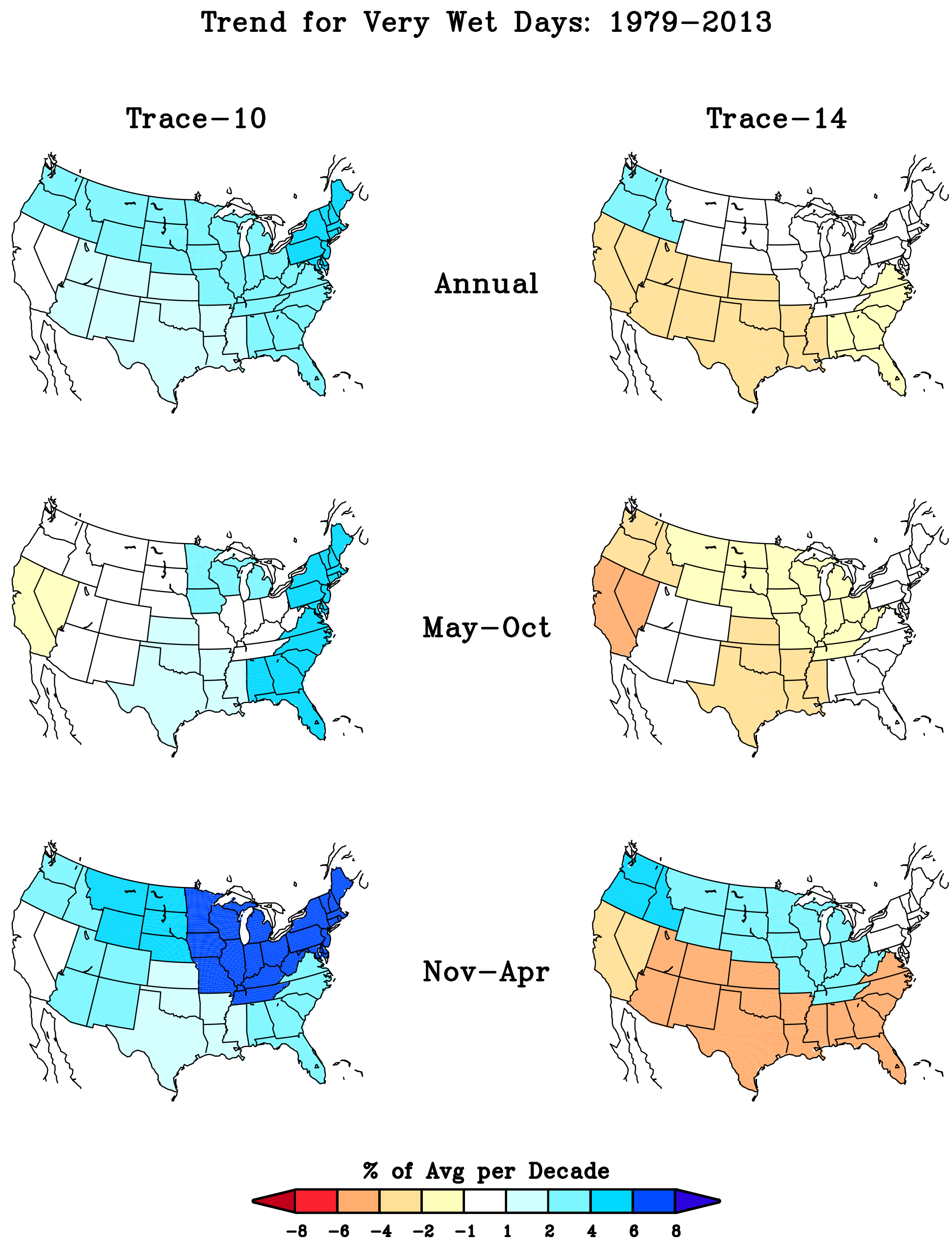


FIG. 7. The 1979–2013 changes in precipitation (% $\text{decade}^{-1}$) associated with heavy daily events (upper 5%) from (left) CAM4 trace 10 and (right) CAM4 trace 14 historical simulations. Trends are shown for (top) annual conditions, (middle) warm season, and (bottom) cold season. The model trends are based on 20-member ensemble means for each configuration. See Table 1 for description of experiments.

14 (right) SST variability. A large sensitivity to SST forcing is clearly seen, with opposite-signed trends in heavy precipitation occurring over large portions of the United States, both for annual (top) and seasonal (middle and bottom) trend patterns. The trace 10 SST history clearly yields a signal of atmospheric change more akin to the CCSM4 ensemble mean result, whereas the trace 14 history yields a signal of change more akin to the CAM4-O ensemble mean result. These experiments thus clarify the important effect of the observed SST history on the boundary-forced component of heavy precipitation change since 1979. They further indicate that the difference between CCSM4 and CAM-O signals is principally due to the difference in their oceanic boundary forcings, rather than due to a difference in experimental design or sampling error.

While recognizing that the precise details of the observed SST evolution since 1979 differ from that occurring in the trace 14 simulation of CCSM4, the similarity in spatial patterns of observed and simulated heavy precipitation trends nonetheless suggests a similar driving mechanism. The results offer additional evidence in support of an argument that the observed widespread decrease in heavy daily precipitation since 1979 occurring over western and southern sections of the United States is most likely symptomatic of internal decadal ocean variability. This physical variation of the coupled system has likely masked an externally forced signal of increased heavy precipitation.

### d. *Observed and simulated seasonal trends during 1979–2013*

The presence of distinct rainy seasons over portions of the United States warrants diagnosis of the seasonality in precipitation trends related to heavy daily events. The leading harmonic of the climatological seasonal cycle of monthly precipitation (not shown) reveals pronounced wet seasons over the central and northern Great Plains during May–October and the far west during November–April. The northeast United States and much of the southeast receive roughly equal portions of precipitation during warm and cold seasons, dominated by convective systems and remnants of tropical disturbances in summer and large-scale frontal cyclones in winter.

The eastern United States has especially witnessed strong seasonality in heavy precipitation trends since 1979 (Fig. 8, top). Much of the annual increase has been a warm season phenomenon, with weaker trends and even substantial declines in the southeast during winter.

By contrast, most of the decline in precipitation associated with heavy daily events across the far west and South since 1979 has been a cold season phenomenon (there has also been a warm season decline in the far west, but those percentage declines constitute small absolute declines during the climatologically dry summer). The meridional pattern of cold season trends (Fig. 8, top right) appears to be consistent with a large-scale northward displacement in the storm track, with a downward (upward) trend in heavy events across the west (east) and south (north) symptomatic of reduced (increased) winter cyclone frequency. Such an inference is supported by the spatial pattern in observed 500-hPa atmospheric circulation (Fig. 9, top right) that describes a trend toward anticyclonic circulation and high pressure over the southern United States and cyclonic circulation and lowered pressure over west-central Canada. This structure bears resemblance to the pattern of atmospheric circulation related to cold states of the tropical eastern Pacific associated with La Niña (e.g., Hoerling and Kumar 2002).

Little seasonality and little regionality in heavy precipitation trends occur in the historical simulations of CCSM4 (Fig. 8, middle). Trends are upward but weak (less than 4% decade$^{-1}$) in most regions during both seasons. No region shows a radiatively forced decline in seasonal precipitation associated with heavy daily events. In this sense, the two most prominent observed features, namely, strong summertime wet trends in the northeast (about 10% decade$^{-1}$) and strong wintertime dry trends in the south and west appear irreconcilable with an externally forced signal. The latter is most likely an outcome of strong decadal-scale internal ocean driving of southern U.S. heavy precipitation events, as demonstrated in section 3c for annual conditions and to be illustrated further below. A discussion on possible mechanisms contributing to the eastern U.S. summer increase in rains associated with heavy daily events is given in section 4b.

The CAM4-O historical simulations indicate that several seasonally varying features of trends in heavy daily events have been consistent with sensitivity to observed SST variability (Fig. 8, bottom). Notable is the strong forced signal of reduction in wintertime precipitation associated with heavy events across the south and far west. The mechanism is similar to that occurring in observations, involving an atmospheric circulation pattern (Fig. 9, bottom right) that would reduce frequencies in migratory cyclones normally responsible for extreme winter precipitation across the west and Gulf Coast. The wave pattern is likely linked most strongly to the prevailing cold SSTs over the tropical eastern Pacific during the last decade (see Fig. 6), resembling the observed pattern associated with La Niña events. It is well known that midlatitude storm tracks, which deliver the majority of precipitation during winter in the United States, are displaced by such changes in the atmospheric wave structure seen in Fig. 9 (top and bottom right panels) (e.g., Held et al. 1989; Hoerling and Ting 1994) and thus would likely be the proximate cause for the southwest U.S. drying. This SST-forced circulation pattern differs greatly from the circulation pattern associated with external radiative forcing alone (see Fig. 9, middle). The latter is characterized by broadly uniform height rises in the extratropics consistent with a mostly uniform pattern of warming, with little gradients in the height trends that would be required to drive appreciable circulation changes.

The CAM4-O ensemble signal also describes several key seasonality features in heavy precipitation trends over the eastern United States, especially the summertime increase in heavy rainfall. The observed

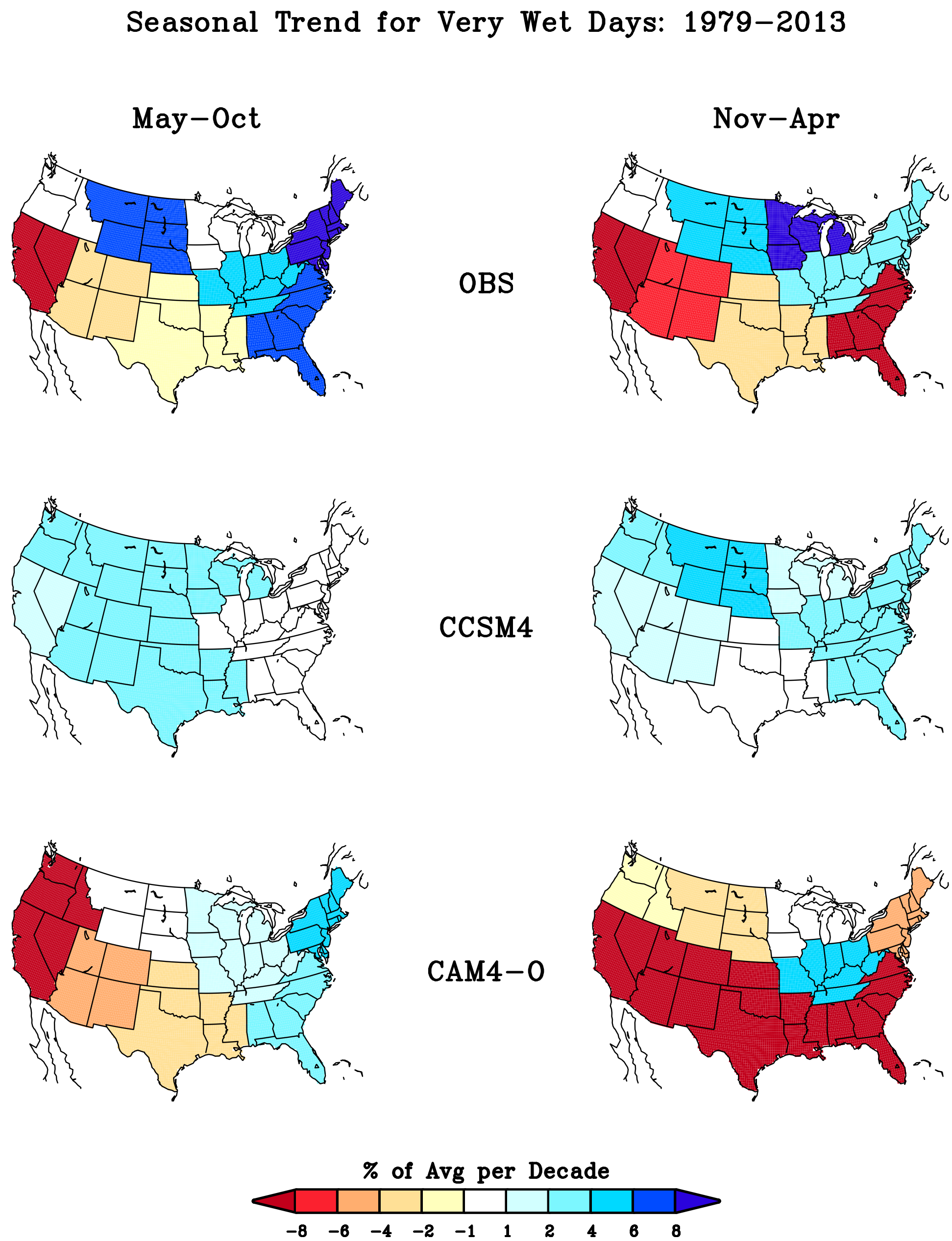


FIG. 8. The 1979–2013 changes in seasonal precipitation (% decade$^{-1}$) associated with heavy daily events (upper 5%) from (top) observations, (middle) CCSM4, and (bottom) CAM4-O historical simulations. (left) Warm and (right) cold season trends. The model trends are based on 20-member ensemble means for each configuration. See Table 1 for description of experiments.

May–October trends in heavy precipitation (upper-left panel of Fig. 8), which have been strong and almost uniformly upward from Florida to Maine, are a pattern found also in the CAM4-O simulations (lower-left panel of Fig. 8). By contrast, no appreciable trends occur in the CCSM4 radiative forced experiments (middle-left panel of Fig. 8) in the east during summer. In the November–April season, the observed trend pattern over the eastern United States is more complicated. The upward trend over the far northeast is not consistent in sign with the ensemble mean AMIP response, though it is consistent in sign with the ensemble mean CMIP response. Over the southeast, the observed downward trend is consistent with an SST-forced signal (an expression of the overall sensitivity to a Pacific decadal oscillation (PDO)-like SST signal in U.S. winter precipitation),

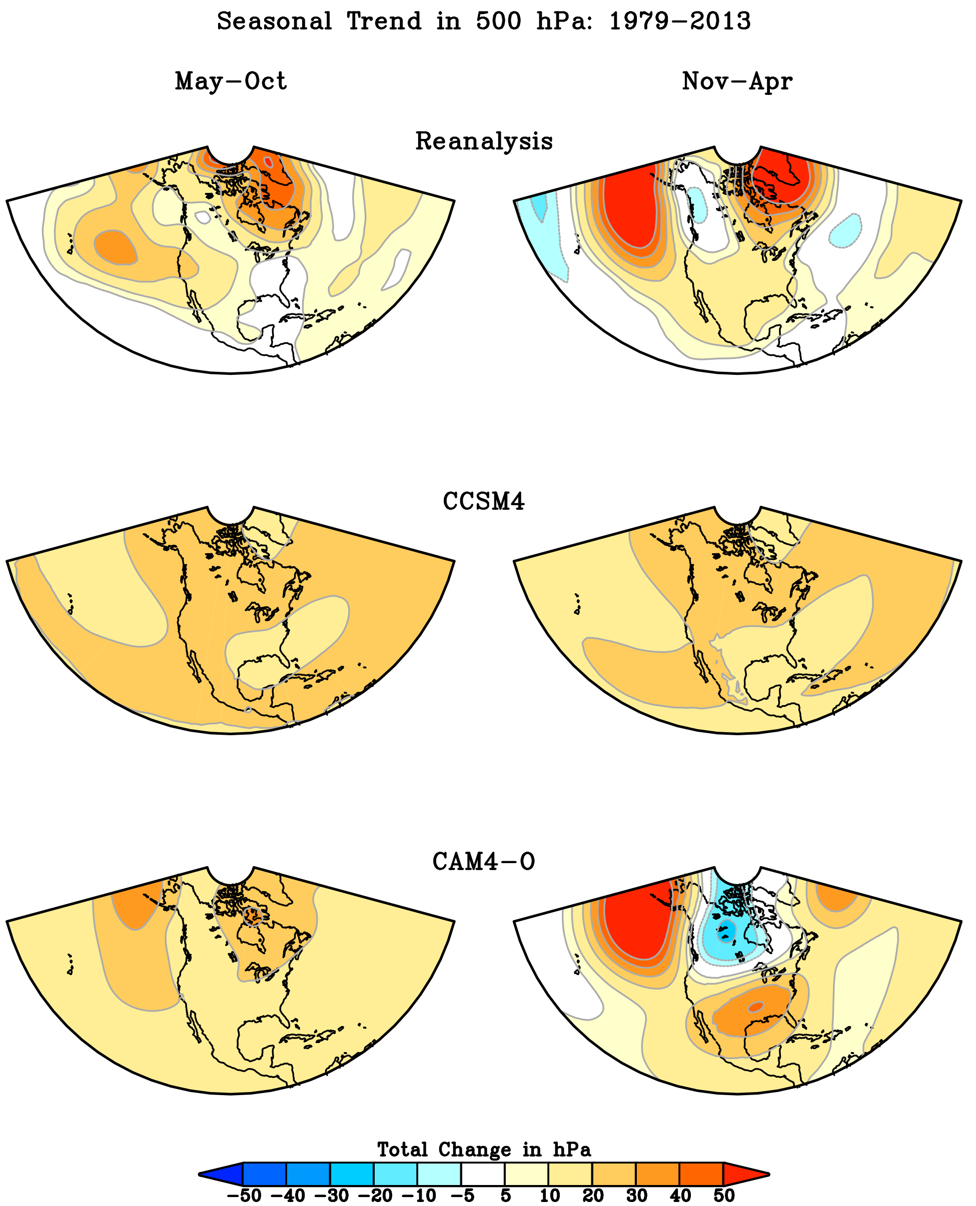


FIG. 9. The 1979–2013 changes in 500-hPa geopotential heights (m) from (top) NCEP–NCAR reanalysis, (middle) CCSM4, and (bottom) CAM4-O historical simulations. (left) Warm and (right) cold season trends. Maps show total change over the 35-yr period. The model trends are based on 20-member ensemble means for each configuration. See Table 1 for description of experiments.

though it is opposite in sign to the radiatively forced sensitivity alone.

Finally, Figs. 10 and 11 compare observed and simulated time series of precipitation falling in heavy daily events for the far northeast and far west regions, respectively. These two areas, one encompassing Pennsylvania, Maryland, Delaware, New York, Connecticut, Rhode Island, Vermont, New Hampshire, and Maine and the other encompassing California and Nevada, have witnessed the strongest trends in the record since 1979 (see Fig. 3). Over the far northeast, most of the observed increase in annual precipitation has occurred during the warm season (Fig. 10, left column), with 10 of the 12 summers since 2002 experiencing anomalously high rainfall contributions related to extreme daily events. The observed positive linear trend during the May–October period is significant at 98%, whereas the winter trend is not statistically significant. There is comparatively little signal of radiatively forced change in the CCSM4 simulations (Fig. 10, middle column),

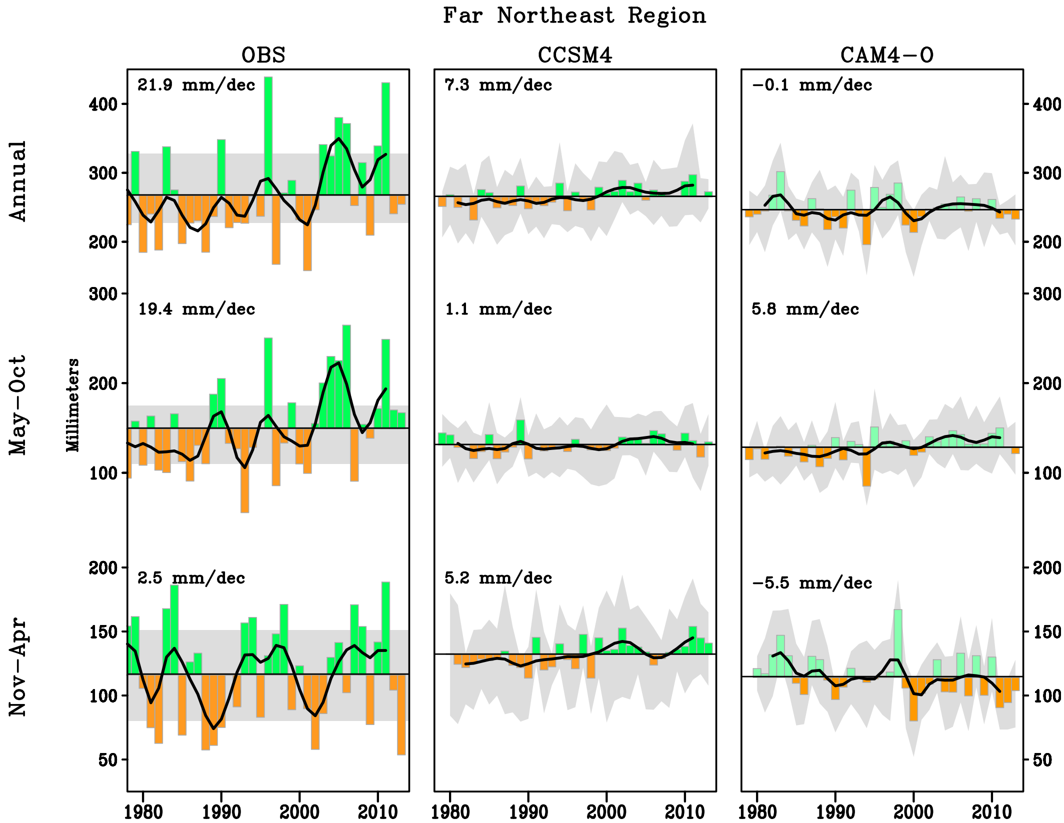


FIG. 10. Far northeast U.S. time series of precipitation (mm) associated with heavy daily events (upper 5%) from 1979–2013 for (left) observations, (middle) CCSM4 historical simulations, and (right) CAM-0 historical simulations. Time series are shown for (top) annual, (middle) warm season, and (bottom) cold season conditions. The statistics for heavy daily events are calculated for an area average of the climate division extending from Pennsylvania to Maine (see Fig. 2). Gray bands denote the interquartile range of heavy daily events based on the entire 35-yr time series for 1979–2013 for (left) observations, and (center),(right) on the 20-member ensemble simulation for each year during 1979–2013. The smooth curve on each time series is a 9-point Gaussian filter. Trend values (mm decade$^{-1}$) are indicated.

with the summer trend being statistically insignificant. During winter, the CCSM4 change signal consists of an increase in extreme precipitation, one that is significant at the 99% level and in quantitative agreement with observations, though recognizing the strong sampling variability in the latter.

By comparison, a strong seasonality of trends in heavy events occurs over the far northeast in the atmospheric model forced by the observed SSTs. While the CAM4-O historical simulations exhibit no appreciable trend in *annual* precipitation linked to heavy daily events, this owes to cancellation between increases in warm season extreme rains and decreases in cold season extremes (Fig. 10, right column). The atmospheric model's signal of a summertime upward trend is appreciably weaker than observed; nonetheless, it is intriguing to note that 10 of the 12 summers since 2002 in CAM4-O ensemble means indicate signals of anomalously high extreme rainfall, a similar behavior to observations. The CAM4-O upward trend in summer is statistically significant at 99%. The physical reason for this simulated upward trend appears unrelated to GHG forcing, insofar as no significant trend occurs in CCSM4. However, aside from the fact that the CAM4-O trend is evidently being forced by a natural pattern of SST forcing during 1979–2013, further research is required to determine if the same mechanisms are operating to account for the statistically significant upward trends in both observations and the AMIP simulation. Likewise, the reason for lack of a significant upward trend in wintertime observed heavy precipitation over the far northeast, despite evidence for a statistically significant increase associated with radiative forcing alone in the CMIP simulation, is unclear and requires further study.

Over the far west, most of the observed decrease in annual precipitation associated with heavy events has occurred during the cold season, with a decrease also occurring during the warm season (Fig. 11, left column).

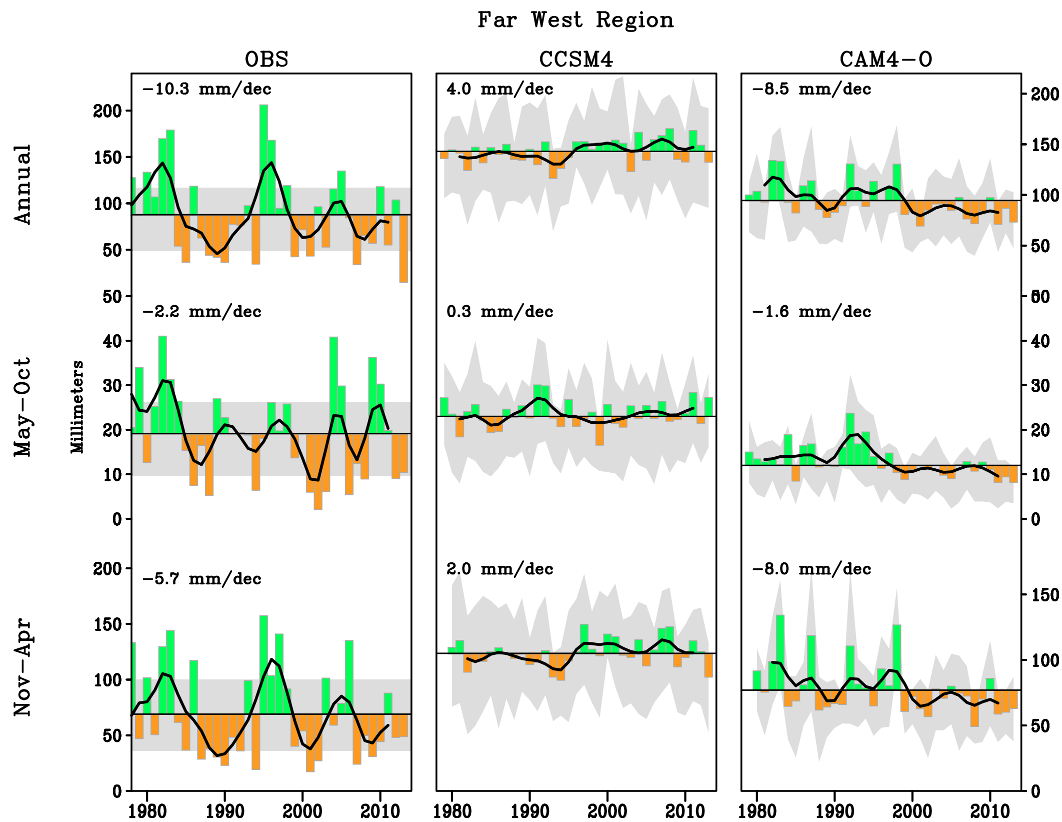


FIG. 11. Far west U.S. time series of precipitation (mm) associated with heavy daily events (upper 5%) from 1979 to 2013 for (left) observations, (middle) CCSM4 historical simulations, and (right) CAM-0 historical simulations. Time series are shown for (top) annual, (middle) warm season, and (bottom) cold season conditions. The statistics for heavy daily events are calculated for an area average of the climate division comprising California and Nevada (see Fig. 2). Gray bands denote the interquartile range of heavy daily events based on the entire 35-yr time series for 1979–2013 for (left) observations, and (center),(right) on the 20-member ensemble simulation for each year during 1979–2013. The smooth curve on each time series is a 9-point Gaussian filter. Trend values (mm $\text{decade}^{-1}$) are indicated.

Owing to the large interannual variability, these observed linear trends are not statistically significant at even a 90% level. The temporal changes since 1979 are not consistent with time-varying signals driven by evolving external radiative forcing (middle columns), which indicate small (but statistically insignificant) increases in precipitation associated with heavy daily events during both cold and warm seasons. The observed time series is consistent, however, with time-varying signals driven by evolving observed SSTs (right columns). We find that CAM4-O ensemble mean downward trends in all seasons and for annual conditions are statistically significant at the 98% level. When combined with the results in Fig. 9, the story of the decline in heavy rainfall events in the far west (and much of the southern United States) is one of a sensitivity to a naturally occurring multidecadal fluctuation in observed SSTs during 1979–2013, the effect of which generates an atmospheric circulation pattern that displaces storm-track activity northward. This dynamical process of drying in the far west has likely overwhelmed a mostly thermodynamic process of extra moisture available to storm systems in a warmed world, a process that alone would likely have resulted in heavier rainfall events.

## 4. Summary and conclusions

### *a. Principal findings*

This study has sought to characterize and explain trends in precipitation associated with heavy daily events, focusing on observed changes since 1979. Concerning a description of the observed changes, most of the long-term increase that has occurred since the beginning of the twentieth century has happened over the northeastern United States, with the most significant rise taking place in recent decades (increase of about 10% $\text{decade}^{-1}$ since 1979). Long-term decreases have occurred in the southwestern United States, though not statistically significant owing to strong multidecadal variability. Since 1979, much of the south and west have witnessed decreases in precipitation associated with heavy events, with a decline rate in the far west near $-10\%$ decade$^{-1}$. Over both the northeast and west, the large-magnitude changes have resulted principally, though not exclusively, from changes in the frequency of occurrence in heavy daily events, rather than from a large change in precipitation intensity per event.

For the period since 1979 specifically, the observed changes in precipitation associated with heavy daily events have been characterized by marked seasonality. The eastern seaboard and especially the far northeast have experienced strong increases in the warm half of year. The mechanisms for the summertime upward trend in very wet days since 1979 were not identified in this study. Our results indicate, however, that they are at least partly forced by internal modes of SST variation during the period, though largely unrelated to anthropogenic climate change. A significant upward trend in anthropogenically forced heavy precipitation is found during winter over the far northeast, though observations show no statistically significant change during the cold season in that region. In the southern and western United States, most of the decrease in precipitation related to heavy daily events has occurred in the cold half of the year. The reduced incidence of heavy rain events appears linked to a northward shift in the storm track owing to a trend in Pacific-North American atmospheric circulation that served to inhibit the typical west–east progression of winter cyclones across the western and southern tier of states. These features of wintertime circulation trends are also found to be unrelated to anthropogenic forcing but have instead been strongly driven by SST variations related to mostly natural internal variability.

We sought to attribute the various characteristics of recent observed heavy precipitation changes to known factors that can drive atmospheric variability and change. Historical climate simulations spanning 1979–2013 using various prescriptions of forcings, either those associated with changes in observed external radiative processes alone or also involving observed ocean surface boundary conditions, were analyzed. The intercomparison of the various CMIP- and AMIP-style simulations conducted in this paper revealed an important effect of the particular trajectory of observed SST variations in causing the regional patterns and seasonally dependent structures of heavy precipitation trends. While an effect of external radiative forcing was also identified, consistent with many previous studies that have examined daily precipitation statistics in CMIP-style historical simulations, the externally driven signal explained neither the regionality nor seasonality in the observed trends since 1979 over the contiguous United States as a whole. A notable exception was over the northern Rockies, where upward trends in both summer and winter heavy precipitation have been observed, a regional and seasonal feature having the same directionality as the ensemble CMIP trend.

### b. *Discussion and conclusions*

Our results rely extensively on a single climate-modeling platform consisting of a coupled model (CCSM4) and its atmospheric component (CAM4). The hierarchy of experiments, and the large ensembles generated for each, were essential to disentangle the effects of internal atmospheric noise, natural modes of internal ocean variability, and anthropogenic GHG and aerosol forcing. However, the robustness of these findings will need to be examined using other models. Some of the findings in this study must thus be tempered by the fact that only a single CMIP model was used, and it will be important to especially revisit the externally forced sensitivity using a multimodel large ensemble approach.

Based on the modeling results, we conclude that anthropogenic climate change has not been a principal factor driving key characteristics of observed changes in U.S. heavy daily precipitation since 1979, though again bearing in mind the caveat of our result's reliance upon a single model analysis. The mechanism of warmer air containing greater water vapor, which, when available to storms, would result in heavier rainfall, is certainly valid. Indeed, global-scale assessments of observed changes since 1950 conclude that more land areas have likely seen increases rather than decreases in the amount of precipitation associated with heavy daily events, with a medium confidence for a human contribution to these observed changes (IPCC 2013). Consistent with this understanding, our results show that the observed increase in heavy daily precipitation over the northern United States during winter since 1979 has the same directionality as the forced signal due to radiative forcing alone. Yet it is unlikely that such a mechanism has been driving many of the major features of the observed regional patterns and seasonal variability in changes during recent decades over the United States as a whole.

Our results provide evidence for an alternative argument for another factor that has been operating in recent decades, namely, that statistics of U.S. heavy precipitation have been sensitive to strong decadal ocean variability since 1979. A strength of the modeling approach used in our study is that a hierarchy of large ensemble simulations was performed that built off a common atmospheric modeling platform (CAM4). We first tested the suitability of using an atmospheric modeling framework for diagnosing heavy precipitation trends occurring in the coupled system. This was undertaken by specifying each of the 20 monthly histories of 1979–2013 SST/sea ice variability occurring in members of CCSM4 within a parallel set of CAM4 integrations. The level of reproducibility of CCSM4 results using the CAM4 two-tiered method was sufficiently good to warrant our more detailed investigation on the importance of particular SST histories on U.S. heavy precipitation trends.

We contrasted the effects of two particular SST histories drawn from the coupled model ensemble: one (trace 10) that resembled the CCSM4's ensemble mean SST change of uniform ocean warming and another (trace 14) that resembled key features of observations, especially an ENSO-like decadal mode of variability having no warming in the eastern tropical Pacific. The signals in U.S. heavy precipitation change for 1979–2013 were very different in response to these two ocean traces, even though each experienced identical external radiative forcing. Further, the U.S. trends in heavy precipitation events in the trace 14 experiments were remarkably similar to those occurring in the observed SST-forced AMIP historical runs. These experiments thus provided several lines of evidence supporting our interpretation that important characteristics of the observed trends in U.S. heavy daily precipitation since 1979 have most likely been symptomatic of internal decadal variability.

The physical cause for the cold season decline in southern and western U.S. heavy daily precipitation was further revealed by consideration of SST-driven atmospheric teleconnections. The AMIP signal in 500-hPa heights revealed a trend in circulation over the Pacific-North American region remarkably similar to that which has been observed during 1979–2013. The pattern, which was also shown to differ materially from the more uniform height pattern occurring in response to radiative forcing alone, has been previously shown to be a characteristic teleconnection occurring in CAM4 when subjected to cold interannual tropical eastern Pacific SSTs. Previous case studies using this model to examine drought causes, one over California (Seager et al. 2014, 2015) and the other over the southern Great Plains (Hoerling et al. 2014), have demonstrated that the far west and south are more likely to be dry in winter when the eastern Pacific is cold. We argue that a similar physical linkage likely explains the downward trend in heavy daily precipitation during 1979–2013 occurring in the AMIP model and in observations.

The physical causes for the strong and statistically significant observed increase in warm season rainfall over the eastern United States have not been resolved in this study, however. While our model simulations indicate that the increase is unlikely related to anthropogenic forcing, it does appear to be at least partly related to a natural internal pattern of SST forcing, though of a character not currently known. Nor has this study identified the mechanism for the strong warm season upward trend in heavy daily rainfall observed in the eastern United States. Kunkel et al. (2012) examined trends in extreme daily rainfall (having 5-yr return periods) and found that the effects of extratropical cyclones are a dominant factor. The extent to which tropical cyclone activity may have also contributed to the observed increase in rainfall associated with the 95th percentile of daily events is a matter requiring additional research. Barlow (2011) has found that rainfall associated with hurricanes contributes substantially to the wettest days, especially along the coast of the northeast. Our results may not be directly comparable for the more modest threshold of 95th percentile events examined herein, though we did find similar upward trends for the more extreme 99th percentile of daily rainfall. It is worth recognizing that notable hurricanes associated with billion-dollar flooding disasters affecting the mid-Atlantic and northeast include Floyd (1999), Isabel (2003), Jeanne (2004), Ivan (2004), Francis (2004), Ike (2008), Lee (2011), Irene (2011), and Sandy (2012), whereas no hurricane-related billion-dollar disaster events affected the northeastern region during 1980–98 (see http://www.ncdc.noaa.gov/billions/events). There is, however, only low confidence regarding a long-term (centennial) increase in tropical cyclone activity, after accounting for past changes in observing capabilities (Hartmann et al. 2013). More research is thus required to quantify how such tropical storms and other mechanisms have contributed to the warm season upward trend in very wet days since 1979.

In conclusion, the paper sought to answer the question whether the recent observed trends in heavy daily precipitation constitute a strongly constrained outcome, either of external radiative forcing alone or from a combination of radiative and internal ocean boundary forcing. We emphasized that the overall spatial pattern and seasonality of U.S. trends has been more consistent with internally driven ocean-related forcing than with external radiative forcing. Yet the magnitude of these forced changes since 1979 was at most equal to the magnitude of observed trends (e.g., over the far west), and, in areas such as the far northeast where especially large upward trends have occurred, the forced signals were several factors smaller. From the perspective of external forcing alone, the observed trends appear not to have been strongly constrained, and apparently much less so than the efficacy of an external driving mechanism surmised in the National Climate Assessment (Melillo et al. 2014).

Our interpretation of the situation regarding trends in U.S. heavy daily precipitation can be useful in building an improved awareness of what is likely to occur over coming decades. While no predictions have been generated in this study, nor forecasts for the future attempted, the characterization of the recent trends as having resulted principally from internal climate variability implies that many of these changes are transitory. Dynamical processes linked to atmospheric sensitivity to particular natural decadal states of the tropical oceans have likely overwhelmed a mostly thermodynamic process in which climate change also alters characteristics of the atmosphere that affect heavy daily precipitation. Yet the influence of anthropogenic effects is expected to increase with time, even at the regional scale. To the extent that the dynamical factors identified as being key operators during 1979–2013 are cyclical on multidecadal time scales, whereas anthropogenic factors are progressively increasing, future patterns of U.S. heavy daily precipitation by the late twenty-first century are very likely to be characterized by increased frequencies and intensities relative to the late twentieth century (IPCC 2013).

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